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DARK ENERGY-DARK MATTER INTERACTION FROM THE ABELL CLUSTER A586

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Abstract. We find that deviation from the virial equilibrium of the Abell Cluster A586 yields evidence of the interaction between dark matter and dark energy. We argue that this interaction might imply a violation of the Equivalence Principle. These evidences are found in the context of two different models of dark energy-dark matter interaction.

1 Introduction

Current cosmological data strongly suggests that the existence dark energy (DE) and dark matter (DM) is crucial for a suitable description of universe's evolution.

Even though observations are consistent with the ΛCDM model, a deeper insight into the nature of DE and DM might require more complex models – in particular considering the interaction between these components. However, so far, no evidence of this putative interaction has been presented. In this work, we argue that data on the cluster A586 shows evidence that DE-DM interaction is an active dynamical factor. Furthermore, we argue that this suggests evidence of violation of the Equivalence Principle (EP).

In what follows, we set the general framework to treat the interaction between DE and DM and consider two very different, phenomenologically viable models: one based on *ad hoc* DE-DM interaction [Amendola 2000], the other on the generalized Chaplygin gas (GCG) model with explicit identification of DE and DM [Bento et al. 2004]. Our observational inferences are based on cluster A586, given its stationarity, spherical symmetry and wealth of available observations [Cypriano et al. 2005]. We also compare our results with other cosmological observations [Guo et al. 2007].

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2 DE-DM Interacting models

Our results are obtained in the context of two distinct phenomenologically viable models for the DE-DM interaction: the DE-DM unification model, the GCG [Kamenshchik et al. 2001], but also a less constrained interacting model with constant DE equation of state (hereafter EOS) parameter $\omega_{DE} = p_{DE}/\rho_{DE}$ (see e.g. Amendola 2000).

We consider first a quintessence model with constant EOS. The Bianchi conservation equations for both DE and DM read – H denoting the Hubble parameter and ζ, the interaction strength:

$$\begin{aligned} \dot{\rho}_{DM} + 3H\rho_{DM} &= \zeta H \rho_{DM}, && (2.1)\\ \dot{\rho}_{DE} + 3H\rho_{DE}(1+\omega_{DE}) &= -\zeta H \rho_{DM}, && (2.2) \end{aligned}$$

for a constant EOS parameter (ω_{DE}), and scaling (η) $\rho_{DE}/\rho_{DM} = \Omega_{DE_0} a^{\eta}/\Omega_{DM_0}$ are assumed. Thus, it follows that the coupling varies as

$$\zeta = -\frac{(\eta + 3\omega_{DE})\Omega_{DE_0}}{\Omega_{DE_0} + \Omega_{DM_0} a^{-\eta}} \tag{2.3}$$

and

$$\rho_{DM} = a^{-3}\rho_{DM_0}\left[\Omega_{DE_0} a^{\eta} + \Omega_{DM_0}\right]^{-\frac{(\eta+3\omega_{DE})}{\eta}}, \qquad \rho_{DE} = a^{\eta}\rho_{DE_0}\frac{\rho_{DM}}{\rho_{DM_0}}. \tag{2.4}$$

We turn now to the GCG model, which is defined by its unified EOS $p_{DE} = -A/(\rho_{DM} + \rho_{DE})^{\alpha}$, with $0 < A \leq 1$ and $0 \leq \alpha \leq 1$, and assuming DE constant EOS parameter $\omega_{DE} = -1$ [Bento et al. 2004]. The splitting into DE and DM, discussed in Bento et al. 2004 together with Bianchi conservation imply a scaling behaviour with $\eta = 3(1+\alpha)$ and energy densities to be

$$\rho_{DM} = \rho_{DM_0}\frac{\rho_{DE}}{\rho_{DE_0}} a^{-3(1+\alpha)}, \quad \rho_{DE} = \rho_{DE_0}\left(\frac{\Omega_{DE_0} + \Omega_{DM_0}}{\Omega_{DE_0} + \Omega_{DM_0} a^{-3(1+\alpha)}}\right)^{\frac{\alpha}{1+\alpha}}. \tag{2.5}$$

3 Generalized Layzer-Irvine equations

We focus, as described in [Bertolami et al. 2007a], on the effect of interaction on clustering as revealed by the Layzer-Irvine equation. We write the kinetic and potential energy densities ρ_K and ρ_W of clustering DM considering the interaction with DE in terms of scale factor dependence

$$\rho_K \propto a^{-2}, \qquad\qquad \rho_W \propto a^{\zeta-1}, \tag{3.1}$$

and we use DM virialization dynamics in an expanding universe described by the generalised Layzer-Irvine equation [Peebles 1993] to obtain [Bertolami et al. 2007a]:

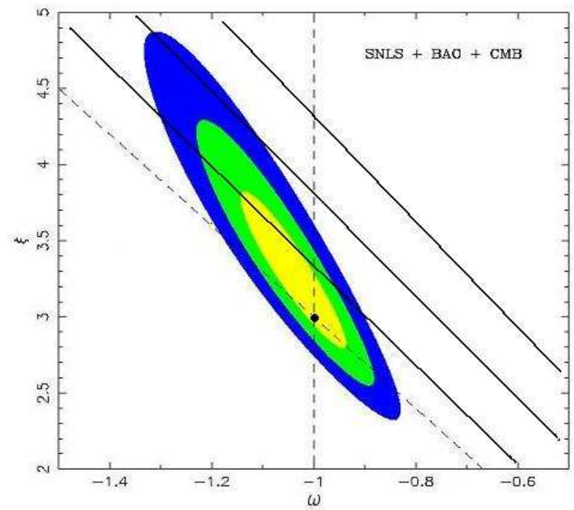

Fig. 1. Superimposition of the probability contours for the interacting DE-DM model in the $[\omega_X,\xi]$ plane (denoted as (ω_{DE_0},η) in [Bertolami et al. 2007a,b]), marginalized over Ω_{DE_0} for CMB, SN-Ia and BAO ($2.66< \xi <4.05$ at 95% C.L.) observations [Guo et al. 2007] with the results extended from [Bertolami et al. 2007a,b], based on the study of A586 cluster. The $\xi = -3\omega_X$ line corresponds to uncoupled models.

$$\dot{\rho}_{DM} + (2\rho_K + \rho_W)\, H = \zeta H \rho_W, \tag{3.2}$$

For the GCG, the scaling allows to just replace $\eta = 3(1+\alpha)$ and $\omega_{DE} = -1$. At equilibrium, in the presence of interaction, $2\rho_K + \rho_W = \zeta\rho_W \neq 0$.

4 Detection of interaction from the observation of A586

Using those models, we have considered observations from the Abell cluster A586 and compared it with other observations [Bertolami et al. 2007a,b].

From Cypriano et al. 2005, we extract: the total mass, $M_{Cluster} = (4.3 \pm 0.7) \times 10^{14}\, M_\odot$ (galaxies, DM and intra-cluster gas), radius, $R_{Cluster} = 422$ kpc at $z = 0.1708$ (angular radius $\Delta_{max} = 145''$) and cluster velocity dispersion $\sigma_v = (1243 \pm 58)\, kms^{-1}$, from weak lensing. From photometry, we can obtain the mean intergalactic distance:

$$< R >= \tfrac{2}{N_{gal}(N_{gal}-1)} \sum_{i=2}^{N_{gal}} \sum_{j=1}^{i-1} r_{ij},$$

where $r_{ij}^2 = 2d^2\,[1 - \cos(\alpha_{ci} - \alpha_{cj}) \cos\delta_{ci} \cos\delta_{cj} - \sin\delta_{ci} \sin\delta_{cj}]$, $\alpha_{ci} = \alpha_i - \alpha_{center}$ and $\delta_{ci} = \delta_i - \delta_{center}$, from declinations and right assentions of a galaxy sub-sample within the projected Δ_{max} where for galaxy i, $\sqrt{\alpha_{ci}^2 + \delta_{ci}^2} \leq \Delta_{max}$. Further

assuming $\omega_{DE} = -1$ and $\Omega_{DE_0} = 0.72$, $\Omega_{DM_0} = 0.24$ [Spergel et al. 2006], we get

$$\rho_K \simeq \frac{9}{8\pi}\frac{M_{Cluster}}{R^3_{Cluster}}\sigma_v^2 = (2.14 \pm 0.55) \times 10^{-10} Jm^{-3}, \tag{4.1}$$

$$\rho_W \simeq -\frac{3}{8\pi}\frac{G}{< R >}\frac{M^2_{Cluster}}{R^3_{Cluster}} = (-2.83 \pm 0.92) \times 10^{-10} Jm^{-3}, \tag{4.2}$$

which allows one to obtain

$$\eta = 3.82^{+0.5}_{-0.47}, \qquad \alpha = 0.27^{+0.17}_{-0.16}. \tag{4.3}$$

Notice that $\eta \neq -3\omega_{DE}$ signals the energy exchange between DM and DE. It is also remarkable that $\alpha \neq 0$ which implies the GCG description is not degenerate with ΛCDM ($\alpha = 0$). We mention that our results (see Fig.1 and Bertolami et al. 2007b) are consistent with the study of Guo et al. 2007 (see also Amendola 2000) where DE-DM interacting quintessence are analysed for compatibility with WMAP CMB [Spergel et al. 2006], SNLS SN-Ia [Astier et al. 2006] and Baryon Acoustic Oscillations in SDSS [Eisenstein et al. 2005].

5 Putative Violation of the Equivalence Principle

Given that the EP concerns the way matter falls in the gravitational field, considering the clustering of matter against the cosmic expansion and the interaction with DE seems to be a logical way to test the validity of this fundamental principle. Both models *predict* departure of homogeneous DM from dust behaviour and have effects that can be interpreted as violation of EP.

The deviation from the dust behaviour of DM due to the interactions with DE leads to evolution of the bias parameter, $b = \rho_B/\rho_{DM}$, on cosmological timescales [Bertolami et al. 2007a] (Fig. 2). Other astrophysical effects also affect the bias so the detection of this drift would require statistics over different z ranges. If we attribute the non-dust part of $\dot\rho_{DM}$ to an additional interaction, the differential of acceleration felt by DM particles can be modeled to be proportional to gravity, the Hubble time and the differential density flux [Bertolami et al. 2007b],

$$\frac{a_{Int.}}{a_{grav.}} = \delta\frac{\dot\rho_{DM} - \dot\rho_{DM}||_{dust}}{\rho_{DM}H} = \delta\zeta\ . \tag{5.1}$$

Gravity is then Baryon/DM composition dependent and this effect depends only on cosmic time. We can now assign the time evolution to a varying G, as seen in Fig. 3 [Bertolami et al. 2007b], to compare with simulations on the fall on the Sagittarius Milky Way satellite on the DM of our galaxy which is consistent with $G_{DM}/G \leq 1.1$ [Kesden & Kamionkowski 2006].

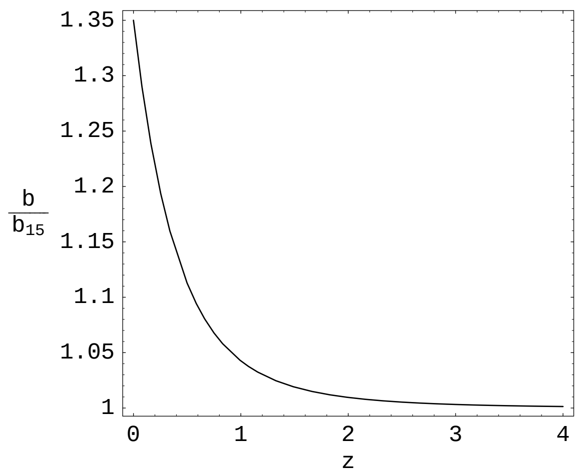

Fig. 2. Normalized gravitationally induced bias parameter as a function of z, where $b_{15} \equiv b(z = 15)$, $z = 15$ is the typical condensation scale and $b = \rho_B/\rho_{DM} = \Omega_{B_0}/\Omega_{DM_0}[\Omega_{DE_0}a^\eta + \Omega_{DM_0}]^{(\eta+3\omega_{DE})/\eta}$.

6 Conclusions

Observations of cluster A586 [Cypriano et al. 2005] suggest evidence of departure from virialization given that A586 is very spherical and relaxed (from its mass distribution and Gyrs without mergers). The generalized Layzer-Irvine equation allows to interpret this departure as due to interaction with DE. We can therefore link the observed virialization to interaction [Bertolami et al. 2007a,b] for two different interacting DE-DM models: an interacting quintessence with constant ω_{DE} [Amendola 2000] and a Chaplygin gas with $\omega_{DE} = -1$ [Bento et al. 2004].

Based on the evidence of interaction, we argue that the Equivalence Principle should be violated as seen through the bias parameter [Bertolami et al. 2007a] and on Baryon/DM asymmetric collapse [Bertolami et al. 2007b]. Our results are consistent with CMB, supernovae and Baryon acoustic oscillations as well as the simulation of the fall of the Sagittarius dwarf galaxy into our own. These results are quite encouraging and suggest that our method should be further employed into other cluster systems (see e.g. [Abdalla et al. 2007]).

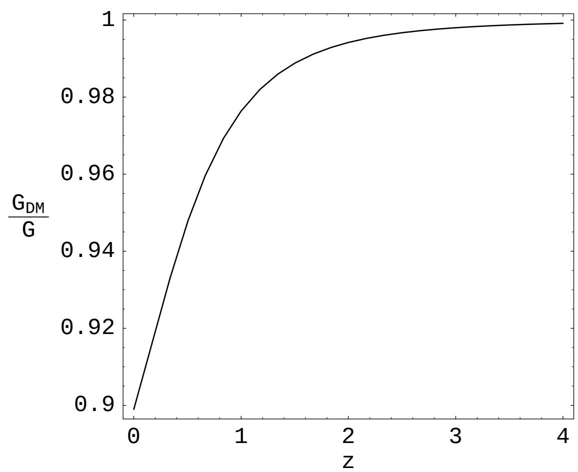

Fig. 3. Evolution with redshift of the ratio of the gravitational coupling for DM and baryons falling on a DM halo, using the varying coupling model discussed in [Bertolami et al. 2007b].

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